

PREDICTION OF APPLE FRUIT FIRMNESS BY NEAR-INFRARED MULTISPECTRAL SCATTERING¹

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ABSTRACT

The objective of this research was to predict fruit firmness by developing and evaluating a multispectral imaging system for real time acquisition of scattering images from apple fruit. A circular broadband light beam was used to generate light backscattering at the surface of apple fruit and scattering images were acquired, using a common aperture multispectral imaging system, from Red Delicious apple fruit for wavelengths at 680, 880, 905, and 940 nm. Scattering images were reduced to produce one-dimensional spectral scattering profiles by radial averaging, which were then input into a backpropagation neural network for predicting apple fruit firmness. The neural network performed best when 10 neurons and 20 epochs were used. With three ratios of spectral profiles involving all four wavelengths, the neural network gave firmness predictions with the correlation of 0.76 and the standard error of 6.2 N for the validation samples.

INTRODUCTION

Firmness is an important textural attribute that determines the acceptability of fresh fruit to the consumer. It is directly related to the structural and/or mechanical properties of fruit tissue. The standard instrumental firmness measurement requires the penetration of a steel probe of a specific diameter into apple flesh for a preset depth and maximum force recorded is used as a measure of fruit firmness. Because of its destructive nature, the measurement can only be used for the sampling purpose and is not suitable for sorting and grading

¹ Mention of commercial products is only for providing factual information for the reader and does not imply endorsement by USDA.

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fruit. Considerable research has been reported on using nondestructive mechanical methods, such as quasi-static force/deformation, impact, vibration, and sonic, to measure fruit firmness (Abbott *et al.* 1997). Most nondestructive mechanical methods measure the elastic properties of fruit such as elastic modulus, which are different from the widely used Magness-Taylor (MT) firmness tester that measures the composite failure strength of fruit tissue during penetration. As a result, nondestructive mechanical methods often do not correlate with MT firmness closely and/or consistently (Abbott and Liljedahl 1994; Shmulevich *et al.* 2003).

Considerable research has been reported on using near-infrared spectroscopy (NIRS) to predict internal quality of fresh fruits, especially soluble solids content (SSC) (Dull *et al.* 1989; Kawano *et al.* 1992; Lammertyn *et al.* 1998; Lu 2001; Lu *et al.* 2000; McGlone and Kawano 1998; Slaughter 1995). Commercial NIRS systems for sorting and/or grading fruit for SSC are available. Use of NIRS for predicting fruit firmness has not been satisfactory (Lammertyn *et al.* 1998; Lu and Ariana 2002; Lu *et al.* 2000; McGlone and Kawano 1998). NIRS provides approximate measure of the absorption of light in fruit, which is related to chemical constituents such as sugar and acid. Absorption and scattering are two basic phenomena when light interacts with biological materials. Scattering is a physical phenomenon that is more closely associated with the structure of fruit tissue. Separation of absorption and scattering is not easy because the two are intertwined in opaque food products; scattering diminishes if absorption is strong for a specific wavelength and vice versa. Cubeddu *et al.* (2001) used time-resolved reflectance spectroscopy to measure the absorption and scattering coefficients of apples, kiwifruit, and peaches. They reported that scattering progressively decreased with increasing wavelength, and it was significantly different among different fruits and between apple cultivars. Cubeddu *et al.* (2001) suggested that scattering could be useful for evaluating fruit firmness. If light absorption and scattering in the fruit can be quantified, it may provide us with an improved means for measuring fruit firmness.

Birth and colleagues (Birth 1978, 1986; Birth *et al.* 1978) explored the potential of using light scattering to measure the quality of agricultural products. Birth *et al.* (1978) used a transmission technique to quantify light scattering for predicting textural attributes of pork. However, the technique is difficult to implement and not suitable for many food products such as fresh fruits.

Several studies investigated light backscattering as a means to predict fruit firmness. Tu *et al.* (1995) used a 670 nm He-Ne laser diode as the light source to generate scattering images at the surface of tomato and apple fruit. A color coupled-charge detector (CCD) camera was used to acquire scattering intensities. The total number of pixels recorded by the red band CCD with intensities above a specified value was counted and related to fruit ripeness and/or firmness.

McGlone *et al.* (1997) used a single channel CCD detector to record the scattering intensity from the surface of kiwifruit generated by a laser diode at 864 nm. They reported that the intensity profile correlated moderately with MT firmness but the standard error was high.

Lu (2004) proposed a new concept of utilizing light scattering to predict apple fruit firmness and SSC. A sharp, focused broadband light beam was used to illuminate a portion of the fruit, generating backscattering images at the surface of the fruit. Spectral scattering images were acquired for wavelengths (or spectral bands) of 680, 880, 905, 940, and 1060 nm. These scattering images were then reduced to one-dimensional scattering profiles by using a radial averaging technique. Ratios of scattering profiles were calculated and used as inputs into a backpropagation neural network to predict apple fruit firmness and SSC. Lu (2004) found that three ratios with four wavelengths were best for predicting fruit firmness with $r = 0.87$ and the standard error of validation (SEV) = 5.8 N and only three wavelengths were needed for SSC predictions.

This paper reports on apple fruit firmness prediction results obtained with an improved multispectral imaging system. The system reported in Lu (2004) used a rotating filter wheel based optical system for acquiring spectral images in sequence, and it was slow in imaging speed (requiring 1 to 5 s exposure time for each spectral image). The multispectral imaging system, as described below, used a common aperture multispectral imaging spectrograph to acquire scattering images for four discrete wavelengths simultaneously. As a result of this improvement, the multispectral imaging system is capable for rapid, real time sensing of fruit internal quality, which is critical for online sorting and grading of fruit. In addition, improvements in image processing algorithms, such as searching for an optimal neuron network (NN) structure and image centers identification, were made to enhance the NN for fruit firmness prediction. And the effects of NN parameters, i.e., neurons and epochs, with different combinations of scattering profiles on fruit firmness predictions were investigated.

METHODS AND PROCEDURE

Multispectral Imaging System

A schematic of the multispectral imaging system for the present research is shown in Fig. 1. The multispectral imaging system consisted of a high performance CCD (charge-coupled device) camera, a multispectral imaging spectrograph that was coupled to the camera, a focusing lens, a computer, and a light source. The CCD camera (Model 4880-21, Hamamatsu Corp., Japan) had a back-illuminated, 512×512 -pixel detector in 16-bit output format. The multispectral imaging spectrograph (Optical Insights, LLC, Santa Fe, NM) split

the beam passing through the focusing lens into four separate, equal beams without losing the original spatial information. Each beam was then passed through a separate interference filter and projected onto a quadrant of the CCD detector. As a result, spectral images at four discrete wavelengths or bands were acquired simultaneously. This special feature makes it possible to perform realtime multispectral imaging. The broadband beam was generated by a 250 W quartz tungsten lamp with a DC control unit (Thermo Oriel, Stratford, CT). The actual beam size used in this research was 1.6 mm with a full divergence angle of 0.024 radians. The beam incident angle was 17° .

As a light beam hit the fruit, most of the light penetrated into the fruit and then scattered in different directions. Some of the light scattered back and reemerged from the surface adjacent to the incident point, generating scattering images at the surface of the fruit (Fig. 2). The multispectral imaging system captured scattering images from the fruit surface over a 25 mm diameter area in 0.25 s. In this research, four bandpass filters were used: 680, 880, 905, and 940 nm with a bandpass of 10 nm, which were the same as those used in our previous study (Lu 2004).

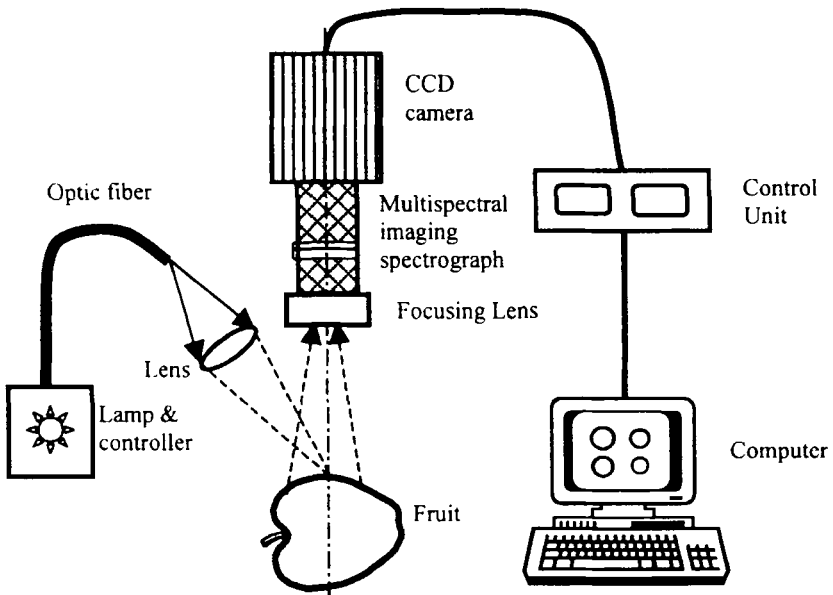


FIG. 1. SCHEMATIC OF THE MULTISPECTRAL IMAGING SYSTEM FOR ACQUIRING SPECTRAL SCATTERING IMAGES FROM AN APPLE FRUIT AT FOUR SPECTRAL BANDS SIMULTANEOUSLY

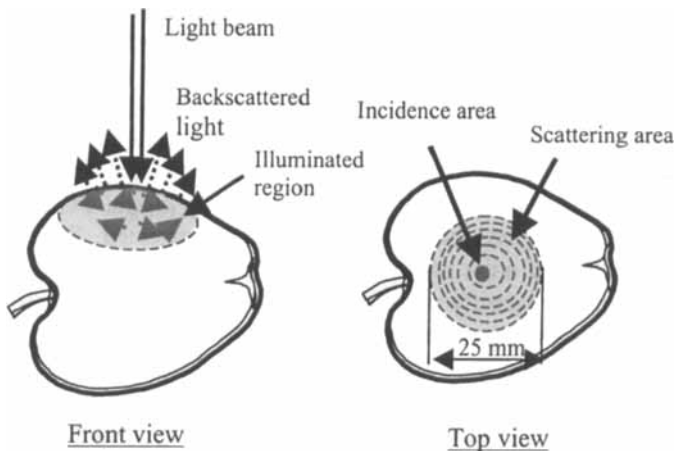


FIG. 2. CONCEPT OF MEASURING SPECTRAL SCATTERING IMAGES FROM AN APPLE FRUIT

Scattering Images Acquisition and Firmness Measurement

Red Delicious apples were harvested from an orchard at the Michigan State University (MSU) Clarksville Horticultural Experiment Station (CHES) on October 7 and 9, 2002 during the normal harvest season. These apples were kept in a commercial controlled atmosphere (CA) storage facility (with 1.5-2% O_2 and 3% CO_2 concentrations at 1C) for five months. They were moved from CA storage to refrigerated air (RA) storage at 1C one week before this study was started.

For each test date, one hundred apples were moved from RA, and they were kept at room temperature ($\sim 20C$) for at least 15 h prior to the multispectral imaging test. Spectral scattering images were acquired from the equator of each fruit with the exposure time of 0.25 s (Fig. 2). After imaging, firmness was measured from the same location that had been used for multispectral imaging with an 11.0 mm steel probe mounted onto a TA.XT2 Texture Analyzer (Stable Micro Systems, Goldalming, Surrey, UK) at a loading rate of 2 mm/min. Maximum force recorded during the 9 mm penetration was used as a measure of fruit firmness. A total of 585 Red Delicious apples were measured over a period of 14 days; the fruit firmness ranged from 23.8 N to 82.8 N, with the average firmness of 52.8 N and a standard deviation of 9.6 N.

Scattering Images Processing

Figure 3 shows four typical spectral scattering images acquired from an apple fruit. The scattering images were highly symmetric with respect to the light incident point and, hence, they could be reduced to one-dimensional scattering profiles. This would result in a significant reduction in data size and greatly improve the signal-to-noise ratio. To obtain scattering profiles, it was necessary to find the incident center for each scattering image. Pixels with the intensity greater than a given threshold value were first selected. The center for each of the four selected areas was found from the four scattering images using the weighted center of gravity method (Weeks 1996). Once the four centers were determined, scattering profiles were obtained by radially averaging all pixels within each circular band of a specified width (or pixels) (Fig. 2). Each circular band had a width of three pixels or 0.72 mm. After completing the radial averaging, each spectral scattering profile was represented by 17 data points only, covering 12.2 mm radial distance. The data points within and adjacent to the incident area were not useful for firmness predictions because they were either saturated or unstable (Lu 2004). Three data points, covering the 4.3 mm diameter central area, were removed from the center; subsequently, only 14 data points were left to represent each scattering profile.

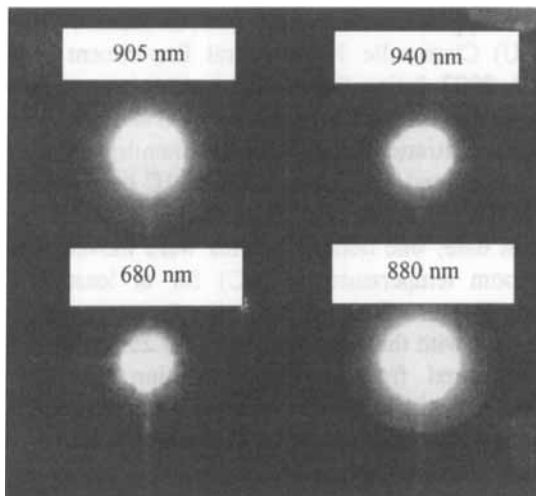


FIG. 3. FOUR SCATTERING IMAGES ACQUIRED SIMULTANEOUSLY FROM AN APPLE FRUIT FOR WAVELENGTHS AT 680, 880, 905, AND 940 nm WITH A BANDPASS OF 10 nm

Neural Network Predictions

A backpropagation neural network (NN) with one hidden layer was used for predicting fruit firmness. Our previous study (Lu 2004) showed that among several data input formats, ratios of scattering profiles were most effective for predicting fruit firmness. The apple samples were first divided into two groups: 4/5 for developing a NN calibration model (the training set) and 1/5 for independent validation (the validation set). An outlier detection criterion was applied to scattering profiles data for the training set to remove extreme samples (outliers). A sample was considered an outlier if its absolute residual value was greater than three standard deviations from the mean value for the training samples at individual wavelengths (Workman 2001). As a result, about 3% of the total training samples were removed. The outlier detection procedure was, however, not applied to the validation set.

After the outlier detection had been completed, an extensive search was performed to determine the optimal set of neurons and epochs with different combinations of scattering ratios as inputs for the NN model. Based on our previous experience, five neuron levels (5, 10, 20, 30, and 40) and four epochs (10, 20, 40, and 80) were used. With the four scattering profiles, a large number of ratio combinations could be generated. To test all ratios combinations for different neurons and epochs would require a significant amount of computational time and was also unnecessary. In this study, six three-ratio combinations were chosen, based on preliminary tests for all combinations of scattering profile ratios (i.e., one, two, and three) with 10 neurons and 20 epochs. Consequently, a total of 120 sets of NN parameters and inputs (5 levels of neurons, 4 levels of epochs, and 6 ratio combinations) were used. For each set, cross validation was run to determine the optimal NN structure. Ten percent of the training samples were left out to monitor the NN and the remaining samples were used for training the NN. The NN was run for ten times during the cross validation. Ten replications were needed because each time when the NN was run, initial weights were randomly assigned, which would lead to different output results. The NN performance was evaluated by calculating the standard error for monitoring (SEM) and the correlation coefficient r for the monitoring samples. After completing NN runs for the first set of monitoring samples, they were put back into the training set and another 10% samples were taken out as a new monitoring set. This cross validation procedure was repeated until all training samples had been taken out once. Once the cross validation procedure was completed for a given set of NN parameters and inputs, the average SEM and r from the monitoring samples were calculated over the 100 NN runs (10 sets of monitoring samples each with 10 replicates). The SEMs and r 's were compared for all 120 sets of NN parameters and scattering profile ratios. The best NN was selected based on the minimal SEM value. Once the

best NN structure was determined, the NN was run again for ten times with all training samples. Among those 10 replicates, the one with the lowest standard error, designed as the standard error for calibration or SEC, was selected as the final calibration model for predicting fruit firmness. This calibration procedure, while requiring considerable computational time, would ensure that the selected NN was optimal and trained properly (Ding *et al.* 1999).

After the NN calibration model had been established, it was then validated with the validation set of samples, from which r and SEP (standard error for validation) were obtained.

RESULTS AND DISCUSSION

Figure 4 shows scattering profiles for Red Delicious apples for the four wavelengths of 680, 880, 905, and 940 nm. Because the photon conversion efficiency of the CCD camera was different for different wavelengths, the intensities shown in each graph do not necessarily reflect the actual backscattering intensities at the surface of the fruit. Overall, scattering profiles at 680 nm, which corresponds to the chlorophyll absorption wave band, showed larger variations among the test fruit samples. For the other three wavelengths, scattering profiles were relatively consistent with less variation between apple fruit.

Firmness predictions were influenced by the number of neurons and epochs used for training the NN. Figure 5 shows how firmness predictions, as measured by r and SEM, changed with neurons and epochs for the scattering profile ratio combinations of F1/F4, F4/F2, and F4/F3, where F1 through F4 represent scattering profiles at wavelengths of 680, 880, 905, and 940 nm, respectively. Within the range between 10 and 80, the epochs of 20 gave best firmness predictions in terms of r and SEM. Firmness predictions became considerably worse when the epochs were 40 and 80. The number of neurons also influenced the performance of the NN model (Fig. 5). Best firmness predictions were obtained when 20 epochs and 10 neurons were used in the NN. After the number of neurons exceeded 10, firmness predictions started to deteriorate.

The NN was able to predict fruit firmness with $r = 0.79$ and $SEC = 5.7$ N for the calibration samples when three ratio combinations (F1/F4, F4/F2, F4/F3) were used (Fig. 6a). The correlation coefficient and SEV for the validation samples were 0.76 and 6.2 N, respectively (Fig. 6b). The three ratio combinations selected in this study are different from those that were used in our previous study (Lu 2004). This could be due to the fact that the current multispectral imaging system used a common aperture multispectral imaging device, in contrast to the rotating filter wheel used in our previous research.

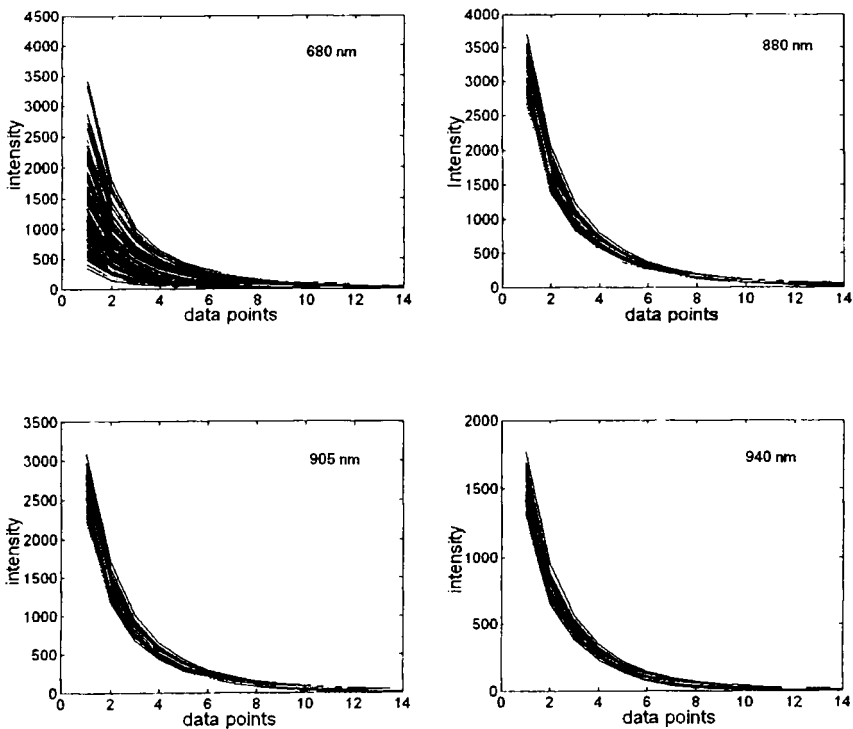


FIG. 4. SCATTERING PROFILES FOR RED DELICIOUS APPLES AFTER RADIAL AVERAGING FOR WAVELENGTHS OF 680, 880, 905, AND 940 nm

The first three data points are not included in the plots and each data point in the horizontal axis represents an actual radial distance of 0.72 mm.

Firmness prediction results from this study are respectable in terms of r and SEV. But these results are not nearly as good as those reported in our previous study (Lu 2004), in which we had $r = 0.87$ and $SEV = 5.8$ N. The current multispectral imaging system was less efficient in receiving light due to the use of the multispectral imaging spectrograph, which would negatively affect the scattering size and the signal to noise rate. Studies of McGlone *et al.* (1997) and Lu and Ariana (2002) suggested that firmness predictions tend to improve with the increasing scattering distance. The optical method proposed in this study is indirect measurement of fruit firmness. Since light scattering and absorption of apple fruit is affected by such factors as cultivar, orchard or location, season, and postharvest handling and storage, some variations in fruit firmness prediction from study to study should have also been expected.

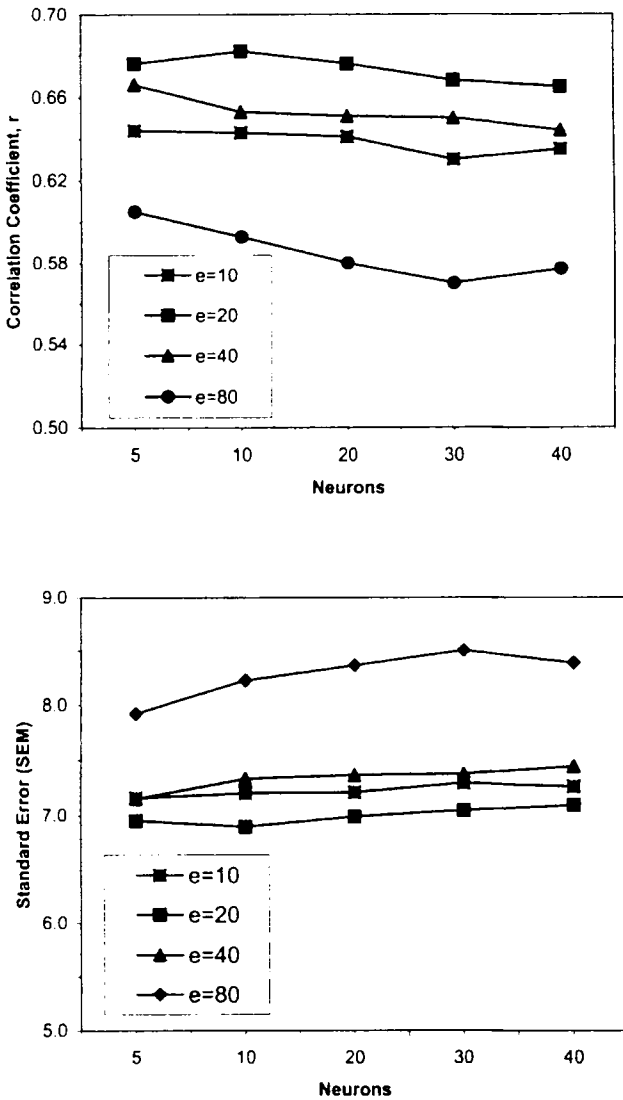
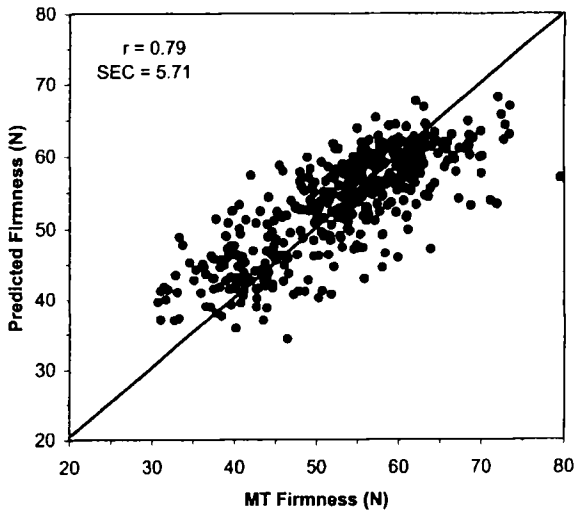
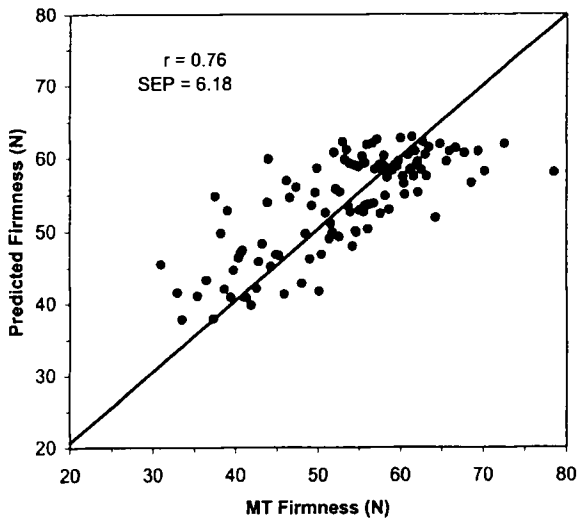


FIG. 5. EFFECT OF NEURONS AND EPOCHS (e) ON NEURAL NETWORK (NN) FIRMNESS PREDICTIONS FOR RED DELICIOUS APPLES, AS MEASURED BY r AND THE STANDARD ERROR FOR MONITORING (SEM)

NN results were obtained with the ratio combinations of F1/F4, F4/F2, F4/F3, where F1 through F4 represent scattering profiles for 680, 880, 905, and 940 nm, respectively. During the cross validation for determining the optimal set of neurons, epochs, and scattering ratio combinations, 10% of the training samples were left out to monitor the NN, and this procedure was repeated until all samples had been used once. NN runs were replicated ten times. Hence each data point in the figure was averaged over 100 NN runs.



(a)



(b)

FIG. 6. COMPARISON OF NEURAL NETWORK PREDICTIONS WITH MAGNESS-TAYLOR (MT) FIRMNESS MEASUREMENTS FOR THE TRAINING (a) AND VALIDATION (b) SETS OF RED DELICIOUS APPLES

Three ratios of scattering profiles (F1/F4, F4/F2, F4/F3) were used, where F1 through F4 represent scattering profiles for the four wavelengths of 680, 880, 905, and 940 nm, respectively.

This study showed that multispectral scattering is useful for assessing fruit firmness. The technique is nondestructive and rapid, and can be easily adapted to the existing packing facilities for sorting and grading fruit. Further research is needed to understand and quantify the effect of such factors as cultivar, orchard, geographical location, and season on firmness predictions. Improvement in the multispectral imaging system is also needed so that better scattering images can be acquired over an even greater scattering area for all four wavelengths. The lighting unit used in this study was relatively inefficient in delivering light to the fruit. An improved lighting unit that is capable of delivering a high quality beam with desired size and characteristics is critical for fruit firmness prediction.

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